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SOME SPECULATIONS ON THE CONSTRUCTION OF ARTIFICIAL PLANETS

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The construction of artificial planets as a possible method of obtaining habitable locations for the long term development of human society would be a logical progression from either terraformed planets or large colonies of the O'Neill type. While clearly any discussion of such systems would be speculative, it is possible to consider some key high level trade offs for artificial planets. It is concluded that an object with a large platinum, iridium, and osmium core, which is about the size of the Moon but with a mass close to that of the planet Mars would be the optimum design. From this an outline of the main characteristics of such a planet is presented, together with some thoughts about its construction, development and viability. It is concluded that if artificial planets were ever to be produce they would need to be constructed by processes very different from those found in nature.

Keywords: Artificial planets, terraforming, solar mining

1. INTRODUCTION

The concept of artificial planets has mostly been confined to the realm of science fiction; and not always very serious science fiction. For a British audience the planet of Magrathea, whose trade was selling designer planets (with its award winning designer of fjords, Slartibartfast) outlined in the comic science fiction "The Hitchhiker's Guide to the Galaxy" [1] has entered popular culture. However, while such systems are clearly highly speculative, they are not outside the realm of physical possibility. Further, some conclusions on the key design issues can be tentatively determined even at this early stage.

Artificial planets would perform the same function as O'Neill space colonies [2] and terraformed worlds, that is to provide a pleasant habitable environment suitable for people to live in on a permanent basis. The defining feature of an artificial planet over an O'Neill type space colony is that gravity is achieved by mass rather than centrifugal force. A consequence of this that the atmosphere would be retained by gravity rather than a pressure vessel, and the other aspects of environment control, radiation, and meteoroid protection would mimic the natural systems of the Earth. This definition and the place of artificial planets in the over evolution of the space infrastructure is discussed in a companion paper [3].

2. SIZE TRADE OFF

It is assumed the design requirement for an artificial planet would call for the same surface gravity as the earth. The size of the planet can then be varied by altering the material from which the core is constructed and hence its average density. The planet's radius (r) is linked to average density (ρ) by the relation:

$$r = \frac{3g}{4\pi G\rho} \tag{1}$$

Where g = surface gravitation acceleration and G = Universal gravitation constant.

The key concern in constructing the planet is the amount of mass that will require to be moved. Getting value for each kilogram invested is clearly desirable and, since the purpose of the planet is to obtain area for living, the mass invested per square meter of planet surface area created is an important factor. The mass of the planet (M) for a surface gravity of g is given by

$$M = \frac{gr^2}{G} \tag{2}$$

When equation 2 is divided by surface area ($A = 4 \pi r^2$) we get a measure of the mass effectiveness

$$\frac{M}{A} = \frac{g}{4\pi G} \tag{3}$$

This shows that mass per area of planetary surface for a given surface gravity is independent of the planet's size. Therefore decisions on the size of planet can be based on factors other than mass efficiency.

Another key consideration is the total amount of material invested in construction before completion of the planet and thus a return on the investment. The lower the total mass of the planet the sooner a sellable product is available. Figure 1 shows the planet's total mass plotted against radius for a surface gravity of 1 g. This shows the r^2 relation in equation 2 over a range of average densities and clearly smaller denser planets have much lower masses, with better than an order of magnitude lower than the earth achievable with realistically sized planets.

The surface escape velocity is another design major design factor and this is plotted as a function of radius in fig. 2 - again for bodies with a surface gravity of 1 g. For ease of transportation to and from space the objective is to lower the escape velocity as far as possible. This is another argument for making the planet small.

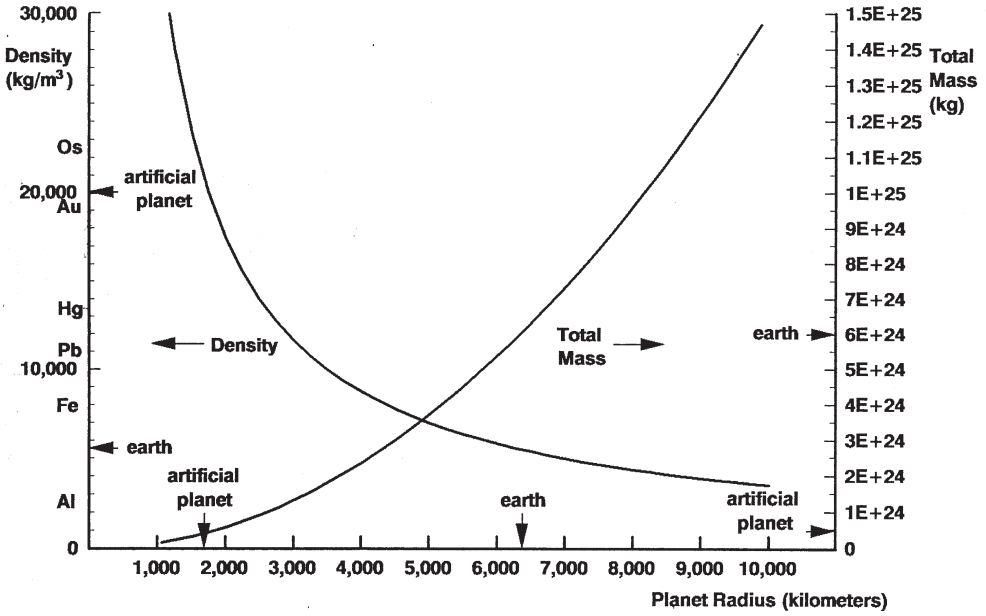

Fig. 1 Mass and Density of Earthlike Planets.

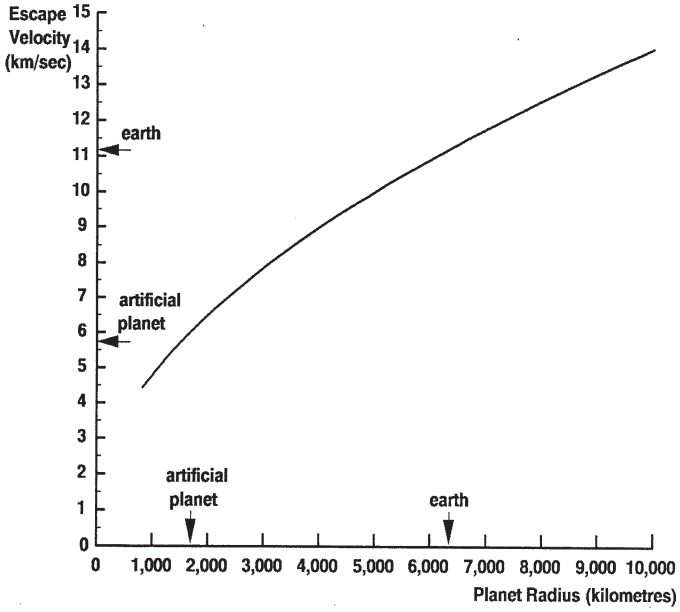

Fig. 2 Escape Velocity Vs Radius for a 1g Surface Gravity.

However, the planet needs to have a high enough escape velocity to retain its atmosphere of nitrogen and oxygen. Given that the mass of the whole planet can be transported by the space infrastructure, and that mass would be continually added by meteorites it is assumed that atmosphere loss could be made up relatively easily and therefore some leakage would be acceptable. A holding time (the time for the atmosphere to decay to 1/e of its original value) of around a million years would seem reasonable in this context. This requires escape velocities in the region 4000 m/sec to 5000 m/sec.

The final factor determining size is the achievable average density (ρ), which to make the planet small should be as high as possible. The highest density atomic materials lie around 20,000 kg/m3. The elements with densities above 19,000 kg/m^3 are:

Tungsten	19,300 kg/m^3
Gold	19,320 kg/m^3
Platinum	21,450 kg/m^3
Iridium	22,420 kg/m^3
Osmium	22,570 kg/m^3

So there are there are several suitable materials with a mixture of platinum, iridium and osmium being the likely choice. These follow one another in the atomic table with atomic masses between 190 and 196. Using this mix as the core material and after accounting for the much lighter rocky mantle it should be possible to achieve an average density of 20,000 kg/m^3. It this maximum achievable density that determines the minimum size a practical artificial planet can be - that is around 1700 km radius.

Table 1 list the main physical characteristics derived for such an artificial planet and compares them with the Moon, Earth and Mars. It can be seen that the planet is a similar size to the Moon, but has total mass closer to Mars. The escape velocity of 5.8 km/sec is more than sufficient to retain the atmosphere while being conveniently low for rocket transportation - single stage to escape being easily achievable even with late 20th century rocket technology.

3. SOME FEATURES

It is assumed that the artificial planets would be located between the orbits of Mars and Venus, which broadly represent the region in which a planet will have a surface temperature compatible with a comfortable life. The precise control of the surface temperature could be achieved both by orbit distance and by varying the amount of greenhouse gases in the atmosphere.

The design objective would presumably be to make the surface conditions a close as possible to earth. To ensure the weather system dynamics working in an earth-like manner some of the surface (probably about half) will need to be ocean. Leaving about 20 million square kilometres of land surface (13% of the earth's land surface). Given that it should be possible to arrange the position of land masses and oceans to maximise the desirable "real estate" it should expect to support a high population density - say 100 people per square kilometre (4 times the USA, same as France, and half the UK). This would give a total population around 2 billion people.

If we assume a total migration input of a billion people and an average share in the planet of $100,000 per person, then the saleable value of the planet would be in the order of $10^{14}.

TABLE 1: *Main Physical Characteristics of an Artificial Planet.*

	Artificial	Moon	Earth	Mars
Radius (km)	1700	1722	6378	3394
Surface Area (km^2)	3.6×10^7	3.7×10^7	5.11×10^8	1.45×10^8
Average Density (kg/m^3)	20000	3300	5500	3950
Total Mass (kg)	4.3×10^{23}	7.4×10^{22}	6.0×10^{24}	6.5×10^{23}
Escape Velocity (km/sec)	5.8	2.3	11.2	5.0
Surface Gravity (m/sec^2)	9.8	1.7	9.8	3.7

It may prove necessary to provide the ocean tides to induce dynamic weather and ocean activity. This could be achieved by building the planets in pairs orbiting each other. To keep forces on the ocean similar to those on earth the higher mass of the artificial planet compared to the moon must be accounted for. As a result the orbit should be something like 3 times further away which gives an orbital radius of around a million kilometres. Such an orbit would have a very slow orbital speed of 170 m/sec and a long orbital period of 429 days - which is likely to be longer than the planetary pair's orbital period about the sun.

Regrettably the companion planet would not be a very spectacular object in the night sky, with only a third the angular diameter of the moon from earth. While it would appear as a solid disk it is unlikely that it would be possible to see much in the way of surface features at that distance. It would also never produce a total eclipse.

Assuming a 24 hour day on the artificial planet, stationary orbit is at a radius of 17,000 km (altitude 15300 km) about half that for the earth. While this does not make the engineering of space elevators trivial, it is clearly easier than on earth and any industrial capability that can contemplate the construction of planets could hardly cavil at adding a space elevator. The land masses on the planet could be arranged for the stable orbital locations to coincide with convenient ground sites. Together with the low escape velocity the interaction of the planet with the rest of the space economy could be sustained at a volume suitable for major trading activity.

4. CONSTRUCTION

4.1 The Construction Process

The main material source for the planet is assumed to be the Sun. Only the Sun and the gas giants contain enough material for new planets. The gas giants have two problems. Firstly a significant construction program would have a marked effect on the planet and secondly the material is cold and would need to be directly mined. By contrast thousands of planets could be constructed from solar material without any significant impact on the sun and the solar material is in a plasma state making it manipulate-able with magnetic fields.

Figure 3 outlines a speculative functional diagram of a planet construction plant. Material from the outer regions of Sun may be scooped by magnetic fields (in a similar manner to a Bussard Interstellar Ramjet) by the processing plant circling the sun at around 10 million kilometres in a retrograde orbit. The material would then be processed in fusion reactors to "cook" the platinum, iridium, and osmium required. These would be "cast" into ingots and then fired from an electromagnetic accelerator into an intercept orbit with the planet under construction.

The core build time is 30 years. This means between 10^{19} kg of material would need to be delivered each day to the planet construction site. As will be shown this produces the shortest overall time for core construction by heating the core to a gas which can be retained by the gravity well of the object.

The assumed production rate is 100 ingots a day, with each ingot being 10^{17} kg mass (around 21 km diameter). With 100 ingots a day and, if the ingot "flight time" before it reaches the planet is of the order of a year, then around 40,000 ingots/per planet under construction will be in transit at anytime. If 10 planets are under construction at any one time this would be around half a million in total – this is an order of magnitude higher of natural large asteroids in that region of the solar system but would probably not unduly interfere with the presumably extensive interplanetary traffic that would exist. If the ingot mass was reduced by an order of magnitude then several million ingots would be in transit which might be a population that could create navigational problems for other space traffic.

The planet construction is achieved by simply allow the ingots to collide with the proto-planet. If the planet's nucleus starts in a highly elliptical orbit with the right energy for the final orbit (i.e. with semi-major axis of roughly 1 AU) the initial collisions would be at relatively low speeds. As this process proceeds the impact velocities of the ingots would rise, due to two factors. The first factor is that biasing the impacts to the trailing side of the proto-planet would circularise the orbit increasing the relative velocity with the ingot orbit. The second factor is that as the proto-planet grows its gravitational well increases and that accelerates the ingots as they fall.

Biasing the impact locations is also assumed to be the method to get the correct spin as well as circularise the heliocentric orbit. The strategy to optimise the departure velocities of the ingots to achieve these outcomes has been left as an exercise for the reader.

In later stages of the construction the kinetic energy of the impacts will produce significant heating. The impact velocities are in the order 10 km/sec giving a daily energy input of the order of 10^{26} J/day. To radiate this heat away the proto-planet would need to be at 6000 K, and therefore in a gaseous state. The gas state is viable as the high atomic weight means the average speed of the atoms (around 2000 m/sec) is still substantially below the escape velocity and the thermal leakage of the "metal atmosphere" would be small during the few years it is at this temperature. The gas state aids the construction process as material losses due ejecta of the impact are minimised.

A 6000 K surface is a similar temperature to the Sun's photosphere so, during this stage of construction, the proto-planets would be a highly visible addition to the night sky.

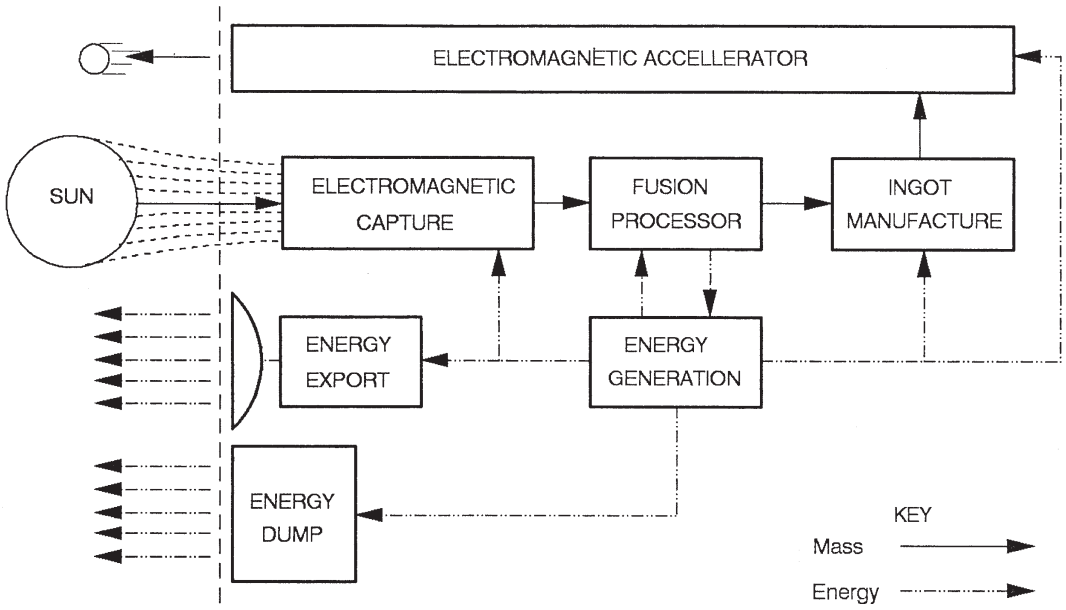

Fig. 3 A function schematic of a planet construction facility.

It is worth noting that two long term heating mechanisms that occur in natural planets can be avoided by minimizing radioactive isotopes and by having the high density material arrive before the low density material so there is little material differentiation once the planet is formed. Therefore, once the core is established, the cooling needs only reject the existing heat energy (in the order of 10^{30} J). So a "pause" in construction would be required, after the core is established, to allow it to cool to a solid surface. This "pause" would be in the order of a century and leave a surface at around 2000 K.

When construction resumes with the final stage where silicates would need to be added to provide the crustal material, and fluids to provide the atmosphere and oceans. These could presumably be "cooked" in the fusion reactor in the same way as the core material. The placing of these last ingots would determine the positions of oceans and continental material.

During the crust construction it is assumed the surface would be kept 2000K encouraging lava to flow, but to achieve this the rate of material deposition must be reduced substantially from the core. Based on the radiative heat loss, the rate should be around 10^{17} kg a day, which (accounting for the reduced density of ingot) would be around 10 impacts a day. A crust of 4 km would weigh around 4 x 10^{20} kg and take around a decade to construct.

The planet then needs to cool to produce surface temperatures around 300K, which would take around 10,000 years. Towards the end of this cooling phase the ocean and atmosphere can be added as desired.

It can be concluded that although the material for the planet can be assembled in decades, the cooling processes dominate the overall construction schedule taking many thousands of years. This timescale is an inherent problem with the impact accretion process and altering the accretion rates would only lengthen the process. The fast construction rates assumed here generate temperatures at the limits of viability, and these very high temperature phases are when the most energy is removed. If the construction were to be slower, it would produces lower temperatures, which in turn would mean lower rates energy removal and longer overall cooling times.

Obviously this schedule dominates the business financing as almost all the investment is at the start of process. We have seen the saleable value of the planet can be estimated at around $\$10^{14}$ so, assuming the money is borrowed on 2% per annum basis, the construction cost would need to be 10^{70} planets to the cent – this is considered an unlikely eventuality.

4.2 The Construction Facility

From the requirements for ingots some conclusions can be drawn on the ingot construction facility that would make them.

The facility requires 10^{14} kg/sec of construction material, which is 100,000 greater than the mass flow in the solar wind, therefore the material must be directly scooped from the Sun's surface. In the direction of the orbit velocity vector the speed difference between the incoming solar material and the construction facility is 115 km/sec this is countered by the ingots departing at 275 km/sec in the opposite direction (the speed that puts them into an elliptical orbit with a semi-major axis of 1 AU). Therefore the construction facility needs to collect more than twice the mass of material from the collector than in ejects as ingots. This addition material would be the propellant in fusion rockets firing along the radial direction towards the Sun. at any time around 10^{20} kg within the magnetic field and to support this the engines need an effective exhaust velocity around 250,000 m/sec

Figure 4 shows a speculative outline of the construction plant. Starting with the electromagnetic accelerator aligned along the centre of mass is some 30 km in diameter to accommodate the 21 km ingot. Assuming an acceleration of 125 g it would take a little under 4 minutes and 31,000 km to reach the required 275 km/sec. The acceleration of the ingots is fundamental to the sizing of the facility and even if 1000 g were assumed of the ingot acceleration the facility would still be still 4000 km in length. It is concluded that the construction facility would by necessity have greater dimensions than the planets it creates.

The main problem for the facility is the enormous amounts of energy the process will produce. The difference in binding energy between hydrogen and helium and the heavier elements around 7 MeV, which means each kilogram of processed mate-

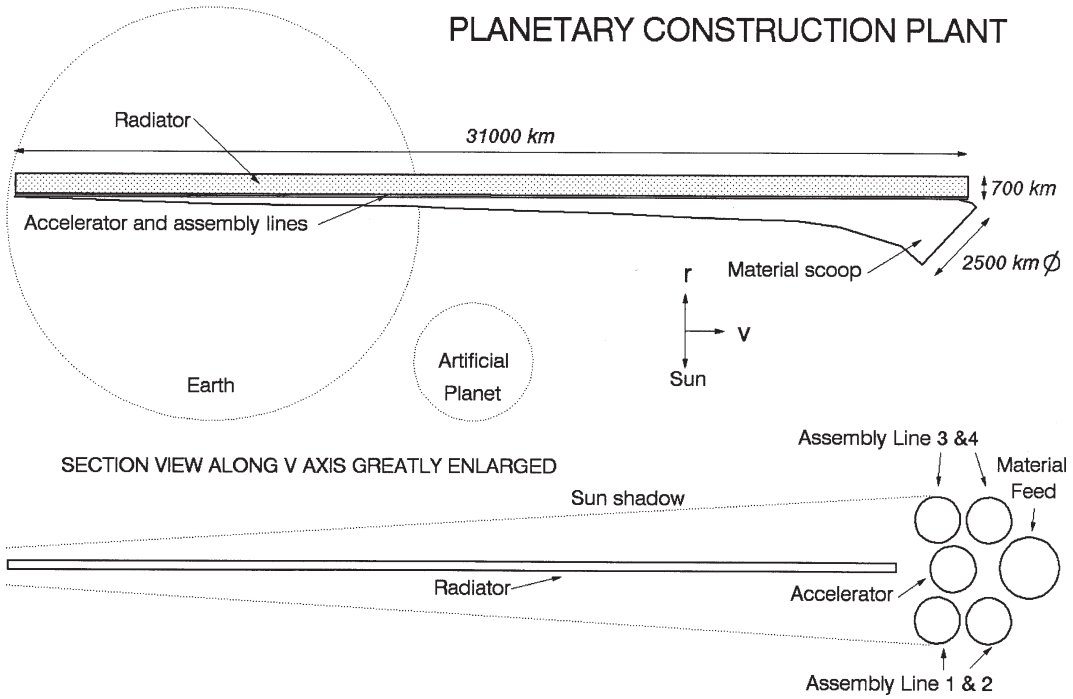

Fig. 4 Planet construction facility.

rial releases around 10^{14} J which is four orders of magnitude greater than the energy required to accelerate the ingots. At the assumed processing rate (10^{14} kg/sec) the total power produced is 10^{28} W. This would be high grade energy and presumably exportable - certainly a civilisation undertaking planetary construction would not be facing any energy constraints! However there would inevitably be a massive amount of unusable waste heat produced which would make the solar heating flux seem trivial. Undoubtedly the main external feature of the assembly plant would be the heat rejection system.

The radiator is shown in fig. 4 within the shadow of the assembly lines and accelerator, which would make it 30,000 km by 700 km giving some 4.2 x 10^{13} square meters of radiator area. If it were running at 1000 K, it would radiate in the order 10^{18} W given this is a factor of 10^{10} lower than the energy being created in the plant there is the possibility this may not be enough. Even altering the radiator dimensions by orders of magnitude does not bring the process into the realms of what is currently considered feasible.

On the Sun side of the accelerator would be electromagnetic scoops and the fusion reactors creating the material for the assembly line. The scheme shows four ingot assembly lines. The required production rate is 100 ingots a day and a single line would need the ingots to travel down the line at 100 m/sec. With four assembly lines the ingots' average speed can be reduced to 20 m/sec and each ingot would take 18 days to be constructed. Each production line would have 450 ingots in production at any time with an average centre to centre separation of about 70 km - making a total of 1800 ingots in the system, which provides a substantial mass for the accelerator to react against. Along each line several material production elements add material to the ingot, probably in cycles of plasma deposition followed by cooling

5. TERRAFORMING

After the 10,000 years production period the planet has a rough rocky surface without any significant weathering and more importantly no ecology.

Thus the final construction phase of the planet would be terraforming by the introduction of a biological ecology. Unlike proposals for terraforming the natural planets the overall conditions are already earth-like. The air is the right density and composition and free water is already available on the surface. The overall environment is essentially the same as a fresh lava field on earth and terraforming would be simply a matter of introducing suitable planets and animals and then giving them time to establish a working ecology.

Although the addition of living organisms cannot be delayed indefinitely as the free oxygen in the atmosphere would tend to be lost this final stage does not have to be done in any particular hurry. Nor does it have to be done on a global scale. Small foothold ecologies using terrestrial organisms adapted for barren environments could be established around initial colonies. In time as the foothold ecologies expand and the number of colonies grows these isolated systems would merge to form a global biosphere.

Given that terrestrial biology can readily supply suitable colonising species that can survive in fresh barren environments (indeed assuming suitable rainfall lava fields can be completely colonised in a matter of decades) and given the likely speed of human colonising activity a complete global coverage could be expected in less than 100 years although longer would be required for a mature biosphere.

6. CONCLUSIONS

The construction of the artificial planets does not seem to represent any fundamental feasibility problem; that is it would not break any laws of physics. This is an obvious conclusion as planets exist and therefore for the laws of physics allow for them. An approach to the creation of artificial planets would be to mimic the natural process that created the natural planets.

A simple trade off highlights that small dense planets offer the best approach, with a practical limit being a 1700 km radius with a mass around 4.3 x 10^{23} kg giving a 1 g surface gravity.

As the only sources of material in the solar system big enough to create planets are composed of hydrogen and helium it can be concluded that artificial planets require the technology of controlled fusion to produce heavy metals – mimicking supernova processes. This is a technology that is not currently understood but it is an essential prerequisite to planet construction. A further conclusion from the scale of the activity is that thermal energy control in the process must be orders of magnitude beyond the current state of the art or that achieved in nature.

It has been concluded that the scale of the production facility must exceed the dimensions of the planet by at least an order of magnitude to accommodate the ingot accelerator and the radiator. If a civilisation can make the construction plant, it could also make O'Neill type space colonies on a massive scale (a class of system designated Ultra-planets [3]) which could provide more habitable surface area, quicker and with much less effort.

If it is assumed the construction is achieved by the process of accreting the planet through ingots impacting the surface in a manner that mimics the natural process of planet formation, then the construction can be achieved in decades. However, due to the heat generated by this construction process, it would take in the order of 10,000 years for the surface temperature to settle to a habitable value. It is therefore concluded that artificial planets would take as long to produce a habitable surface as terraforming existing worlds.

The impact of these factors when considered against alternative ways of creating habitable environments has been argued in reference [3]. Only a society with a major space faring capability including the ability to make space colonies on the O'Neill model [2] would be able to consider such an enterprise. Presumably only a society with a continuing population growth would have the need to undertake it. Further, since the mass invested per sellable square kilometre of surface is much worse than O'Neill type space colonies it is likely that artificial planets would only be considered if such colonies proved to be highly unsatisfactory as locations for the long term evolution of human society.

Consideration of artificial planets is at the far extreme of what can sensibly be considered in astronautics and clearly it is not a subject for even long term consideration. However using our current state of engineering and scientific knowledge we can foresee ways in which it might be accomplished - by mimicking the natural heavy element and planetary formation processes in a faster more controlled manner. However this leads to some fundamental constraints on the technology, physical scale and duration of the acquisition phase, which makes its realisation unlikely. It is concluded that if artificial planets were ever to be produce they would need to be constructed by processes very different from those in nature.

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